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. ..,.,..Annlication of Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) to Determination of Atmospheric Aerosol Optical Depth and Precipitable Watt.r Content

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1,. Introduction. Three fundamental problems of terrestrial solar reflective optical remote sensing can be formulated in general terms as follows: (1) determination of the land and' ocean surface bidii ccl ional reflectance distribution function (BRDF) or directional surface-lea,ving radiance from top-of-atmosphere dire.ctiolial radiance measurements, (2) determination of surface-atmosphere radiative arid material flux interactions, and (3) determination of the temporal and spatial gas absorption and aerosol scat tering proper ties of the atmosphere itself including the radiative (absorption and scattering) properties of clouds. The solution of problem (1) can be most generally, but not exclusively, carried out by usc of an appropriate radiative transfer model together with assumptions concerning lateral and vertical variability of atmospheric properties. Accurate constraint of such models requires detailed knowledge of the absorption and scattering properties of the atmosphere, both spatially and with altitude. In practice, such information is rarely available from independent observations, and departures of the assumed conditions from the actual ones present will lead to errors in the recovered reflectance values. A desirable methodology would certainly be the estimation of the required atmospheric parameters from the TOA spectral radiance measurements themselves. The MISR experiment (Diner, et al., 1991), through interpretation with a full three-dimensional radiative transfer code of multiangle observations of the TOA radiance, will p,cnc.rate estimates globally of both atmospheric optical depth and surface BRDF as part of the NASA EOS program. A recent workshop (Slater and Mendenhall, 1993) summarized the status of the atmospheric correction problem for Landsat imagery: With respect to question (2), the improved estimation of regional land surface evaporation "into the atmosphere is important in understanding land ecosystem functioning (Schmugge and Andre, 1991), and together with determination of Ocean evaporat ion, for climate modelling (Starr and Melfi, 1991). It may, for example, prove feasible to estimate via a material balance model. (Brutsaert, 1982) the regional average surface flux of water vapor into the atmosphere using remote sensing observations of the areally averaged space and time-variabil{[y of atmospheric water vapor column abundance. The procedure was described by Conel and Carrere (1992). The present paper focuses on question (3), specifically derivation of estimates of aerosol optical depth, atmospheric water vapor, and oxygen pressure surface altitude from upwelling near-'l'OA spectral radiance measurements obtained with the Airborne Visible/lnfrared imaging Spectrometer (AVIRIS).

2. Characteristics and calibration Of AVIRIS. AVIRIS is a so-called whiskbroom imaging spectrometer that produces images of spectral radiance in 224 channels (10 nm intervals) between 400 to 2500 nm. The instrument flies aboard the ER-2 aircraft platform at an altitude of 20 km above terrain, At this flight altitude the side-to-side angular field-of-vic,w of ±15° about nadir generates an image swath approximately 11 km in width with pixel size 20 m. The areal coverage rate determined by ER-2 ground speed is approximately 110 km^2/40 seconds.

AVIRIS is radiometrically and spectrally calibrated in the laboratory using an integrating sphere and spectral radiometer (Chrien, et al., 1990). Under inflight conditions, the radiometric calibration is established using a reflectance-based method in which the spectral radiance from a uniform ground target, as determined from the laboratory calibration coefficients, is compared with the spectral radiance calculated at flight altitude at AVIRIS spectral resolution using the MODTRAN atmospheric transmittance code (Berk, et al., 1989). To constrain the code, atmospheric spectral optical depth at nine wavelengths (370-1030 nm, $\Delta\lambda \approx 10$ nm) and water vapor column abundance were determined from solar photometry. The surface target spectral reflectance was measured with a portable spectrometer at the time of overflight. Results of such a recent calibration experiment arc shown in Figure 1 (Green, et al., 1993), Inflight, the laboratory spectral calibration is validated by comparing t I : shapes of atmospheric gas absorption bands determined by the AV11{1S observat ions with band shapes produced from MODT 'l{ AN, Channel positions determined by these two methods usually agree to within 1 nm.

3. Method of aerosol retrieval. Under conditions of low meteorological range the radiance scattered from atmospheric aerosols may comprise a significant portion of the total radiance reaching the AVIRIS sensor. A comparison according (o MODTRAN 2 of the aerosol-scatter'cd radiance with parts due 10 molecular scattering and, to interaction with the both the atmosphere and ground; is given in Figure 2. A nonlinear least square" spectral fitting (NLLSF) algorithm was implemented to est imate the aerosol opt ical depth from" the spectral radiance measurements obtained with AVIRIS. This algorithm optimizes the fit between "the AVIRIS radiance and a MOD' 'RAN 2-modelled radiance with the aerosol optical depth as the primary fitting parameter. Additional adjustable parameters arc magnitude of the surface reflectance, slope of the reflectance with respect to wavelength, and a reflectance model of leaf chlorophyll absorption. Figure 3 shows results of applying the NLLSF algorithm to' a forest target at 120 m elevation, within the Jasper Ridge Ecological Preserve. Jasper Ridge Preserve lies al the foot of the Santa Cruz Mountains 7 km southwest of Palo Alto, Califonria (for locations of sites mentioned refer 10 Figure 9b). A preliminary value for the retrieved aerosol optical depth is 0.42 at 500 nm. This value is compared in Figure 4 to the average optical depths determined by solar photometry for the AVIRIS overflight period using methods described by Reagan et al. (1987) and Bruegge et al.(1 990). Aerosol optical depths were also calculated for the ent ire AVIRIS data set at Jasper Ridge. The values determined (Figure 4) ranged from 0.?7 in the Santa Cruz Mountains at elevation 5S0 m to 0.53 near San Francisco Bay at sea level. Future investigation of this method will focus on sensitivity of the algorithm to: (1) the chosen simple parameterization of surface as a Lambertian reflector, i.e., neglect of the actual surface BRDF in the radiative transfer model, (2) the assumption of plane-])aralkl atmospheric conditions and (3) uniform surface reflectance for a local calculation in the presence of actual lateral variability, and (4) the assumed aerosol model.

4. Surface pressure **height from** oxygen **band measurements.** Accurate compensation for atmospheric absorption from wctl-mixed gases together with the effects of molecular scattering require determinations of surface. elevation. Under assumption of a local]danc.-parallcl atmospheric model an algorithm was developed that asseses the strength of the 760 nm oxygen absorption band resolved in the AVIRIS radiance measurements. Using. the vertical oxygen distribution resident in the MODTRAN 2 model, a relationship was developed between oxygen band strength and surface elevation. The algorithm uses the NLLSF procedure with . spectral radiance measured by AVIRIS and the MODTRAN 2 model oxygen band profile with the following adjustable parameters: equivalent surface pressure elevation; magnitude of the surface reflectance at 760 nm, and slope of the surface reflectance with respect to wavelength at that wavelength. To improve precision of the recoveries the AVIRIS radiance measurements were averaged over 11 by 11 spatial samples. Figure 5 shows rc.suits of the fitting procedure for a dry grass area of the Jasper Ridge Preserve for which an average pressure elevation of 250 m was obtained. The altitude measure.d by altimeter at the time of overflight was 2,80 m (989.6 mb). The approximate elevation of that Site determined from topographic maps was 200 m. The fractional uncertainty in molecular scattering optical depth $\delta\tau_m/\tau_m$ arising from an uncertainty in surface height δh is $-\delta h/\sigma$, where σ is the scale height. For σ equal to 8.25 ton, an error of+ 30 m in elevation gives rise. to a -0.4 % error in τ_m.

An analysis was carried out for a simple algorithm based on the ratio of band depth to average continuum radiance to estimate precision of surface height recoveries from oxygen band measurements. It was assumed that uncertainties arose from noise in the radiance measure.mcnts themselves. For the conditions: meteorological range = 100 km, surface reflectance = 0.?S, and a rural aerosol model, the MODTRAN 2 code yielded the relationship R = 0.64 + '2.07x1 O 'h + 3.77x10"19)2 where R is the band ratio and h is surface elevation in meters. The uncertaint y in surface height recovery σ_h on a per pixel basis as a function of AVIRIS signal/noise (S/N) at 760 nm is given in Figure 6. The current observed inflight S/N at 760 nm is close to 300 which suggests the possibility of elevation recoveries with a precision on the order of 150 m on a per-pixel basis or about 14 m for an 11 by 11 average,.

The oxygen band method applies to geometrically simple optical paths through the atmosphere, but encounters obstacles in the presence of clouds or aerosols, i.e., circumstances in which the single scattering albedo Of individual scatterers is very close [o unity. Under these conditions the photon optical path throught the absorbing interstitial medium can be very great, especially when cloud or scattering layer optical depth is large (van de Hulst, 1980, Ch. 17). This will lead to large values of oxygen absorption and consequentl y erroneous estimates of sl]l'face. height as opposed to determinations made under scatter-free direct path conditions. The discrepancy cited previously at Jasper Ridge, between fic.kl-measured surface height (280 m) and surface height determined from the oxygen band method (2S0 m) may arise from such scattering effects. Future field and model experiments arc planned with AVIRIS and MODTRAN 2 to test the.sc ideas,' and to investigate conditions where oxygen band measurements may actually be used to determine cloud height.

5. '**Atmospheric water vapor.** The strongest at mospheric absorber over most of the AVIRIS spectral range is water vapor (Figure 7), and its abundance may vary greatly both spatially and temporally (Green, c1 al., 199 1; Conel, et al., 1991): To compensate for water vapor absorption using an atmospheric model such as LOWTRAN 7 (Kneizys, et al., 1987) or MODTRAN 2 (Berk, et al., 1989), measurement of total path precipitable water is utilized to scale the resident vertical distribution of atmospheric moisture al each spatial element throughout an image. The first algorithms wc developed for atmospheric precipitable waler estimation from AVIRIS radiance measurements, utilized simple in- and out-of-band radiance ratios of the 940 nm absorption feat ure and the LOWTRAN 7 transmittance code (Conel, et al., 1988; Green et al,, 1989). These algorithms employ the assumption of local lateral atmospheric homogeneity and Lambertian surface reflectance independent of wavelength. They arc thus vulnerable not only to departures of the surface reflectance from the assumed value, but also to: (1) interference from spectral variations from liquid water or other absorption bands present in vegetation, soil moisture, or hydrated minerals at the surface and (2.) incorrect assumptions about other required but unknown parameters such as aerosol load and aerosol type (Carrere and Conel, 1992). To relax the previously required assumption of constant surface reflectance, a NLLSF algorithm was developed based on MODTRAN 2 (Green, et al, 1991) that allowed variation of parameters describing the amount of at mospheric precipitable water, the reflectance magnitude, the reflectance slope with wavelength, and a coefficient that scale.d a predetermined fixed leaf liquid water reflectance spectrum. Aerosol scattering was accounted for by specificat ion of the meteorological range. in the MODTRAN 2 mode.1. A previously developed lcasl-square based model of water vapor recovery employing the Malkmus band model (Gao and Goetz, 1991) did not account for atmospheric scattering. Figure 8 shows the agreement obtained in the present case between the spectral radiance measured by AVIRIS and the. NLLSF spectrum for the 940 nm water band over a green grass target south of Palo Alto. Figure 9a shows the variation of path precipitable water over the site as compared [o surface. cultural features, vegetation, and water bodies represented in the AVIRIS image of Figure 9b.

6. Summary. Algorithms have been described based on the MODTRAN 2 radiative transfer model that give estimates of the absorption and scattering characterist ics of the atmosphere from AVIRIS radiance measurements alone. These characteristics may be used in the model to derive estimates of equivalent surface Lambertian reflectance. A step-by-step validation of the various procedures described will involve: (1) direct comparison of the atmospheric parameters with in-situ measured values, and (2) comparison of the model-derived surface reflectances with surface reflectances measured with portable spectrometers. These studies arc under way.

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Figure captions

Figure 1. Comparison of the MODTRAN-predicted and AVIRIS-measured radiance for the inflight calibration experiment of 30 May 1992.

Figure 2. The total radiance, ground-and-atm osphere-reflec ted, molecular scattered and aerosol scattered spectral radiance components given by MODTRAN 2 for a Lambertian target of 0.25 reflectance at sea level with meteorological range of 5 km and rural aerosol model.

Figure 3. Example of comparison (with residuals) of the best-fit radiance from NLLSF algorithm according to MODTRAN 2. with spectral radiance measured by AVIRIS used for estimation of aerosol optical depth.

Figure 4. The aerosol optical depths at wavelength of 500 nm retrieved with the NLLSF algorithm at Jasper Ridge, CA forest site (JR) and over the elevation range present (Range) in the AVIRIS imagery of Jasper Ridge site compared withinsilu-measured time-avcragcopticaldcpth values, June ?., 1992; 10:15-14:07 PDT.

Figure 5. The fit with residual between the MODTRAN 2 NLLSF spectrum and AVIRIS measured spectrum for the estimation of surface pressure elevation from the 760 nm oxygen band.

Figure 6. Error in the height retrieval from the oxygen band algorithm from noise in radiances measured by AVIRIS. Actual noise/signal (l/S/N) is approximately 300 as determined from laboratory detector dark current measurements. in inset, L_{O_2} is the oxygen band radiance at 760 nm, and L_c is the continuum radiance at 760 nm determined by linear interpolation between radiances to either side of the band. R in the text is equal to L_{O_2}/L_c.

Figure 7. Influence of atmospheric water vapor amount on the upwelling spectral radiance at AVIRIS calculated according to the MODTRAN 2 model,

Figure 8. Fit with residual between the AVIRIS-measured radiance and the NLLSF radiance from MODTRAN " 2 over the 940 nm water vapor absorption band for a green 'grass target at Jasper Ridge Preserve.

Figure 9. (a) Atmospheric water vapor column abundance (atm-cm) over the Jasper Ridge Preserve and surroundings retrieved using the NLLSF algorithm, To convert atm-cm of water vapor to precipitable cm, divide by 1'24S.3. (b) AVIRIS image of the image area in (a) snowing cultural features and vegetation patterns. SLA = Stanford Linear Accelerator; f = fore.s!, dg = dry grass, gg = green grass targets. Gray scale denotes instrument DN. Band 25 = 660 nm.